A PROPULSION SYSTEM FOR A SCIENTIFIC MICRO/NANOSPACECRAFT

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ABSTRACT

A preliminary propulsion system design for a 10-100 kg. micro/nanospacecraft for generic scientific missions is described. The design drivers resulting in this proposed system are discussed as well as current technology developments.

INTRODUCTION

The propulsion system described herein is for the Future Deliveries project of the Deep Space Systems Technology (DSST) program at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. The DSST Future Deliveries project is defined in detail in Reference 1. The specific point design shown is for the second delivery which is a relatively near-term scientific microspacecraft. However, the technology is applicable to a wide range of generic spacecraft from about ten kilograms mass up to several hundred kilograms.

SYSTEM SELECTION

A single propulsion system for attitude control (ACS), thrust vector control (TVC) and delta-velocity (ΔV) burns was desired based on mass and cost. The requirement for multiple ΔV burns precluded a solid propellant system. The magnitude of the ΔV thrust and very low spacecraft power capacity precluded electric and ion propulsion systems. A single system could be designed using cold-gas, hot-gas, monopropellant-liquid or bipropellant liquid propellants. The combined requirements for mass, performance and ACS minimum impulse bit resulted in selection of heated helium as the propellant.

The closest competitor to heated helium is monopropellant hydrazine. The results of the trade study that resulted in choosing heated helium are shown later.

The second-delivery system requirements that drive the design are shown in Table I. Total spacecraft mass, total ΔV and ACS minimum impulse bit were the major drivers.

SYSTEM DEVELOPMENT

The schematic diagram for the second-delivery system is shown in Figure 1. Storage of the helium at 690 bar (10,000 psia) minimizes the size of the tank and takes advantage of the high performance of ultralight composite overwrapped tanks being developed for the Mars missions, Reference 2.

Use of two regulators minimizes the size and mass of the ΔV thrusters while delivering the minimum impulse bit of the ACS thrusters. The high-pressure bypass to the ACS thrusters allows them

TABLE 1

Major Design Driving Requirements

REQUIREMENTS
1. Total Initial Non-Propellant-Related Mass = 21 kg.
2. Total ΔV = 200 m/s
3. Total ACS/SLEW/HOVER Impulse = 92 N-s
4. Redundant Coupled Attitude Control
5. ACS Minimum Impulse Bit of 0.000010 N-s
6. ACS Thrust Level of 0.010 N Per Thruster
7. ΔV Thrust = 1.0 N Per Thruster
SELECTED DESIGN
1. Heated Helium Process Used to Obtain 2492-3257 m/s ISP for ΔV
2. Unheated Helium Provides 1619 m/s ISP for ACS/SLEW/HOVER Pulsing
3. Thrust Vector Control for ΔV Firings Achieved with ACS Thrusters Operating at Higher Pressure in Addition to Off-Modulation of ΔV Thrusters
4. Limited Functional Redundancy

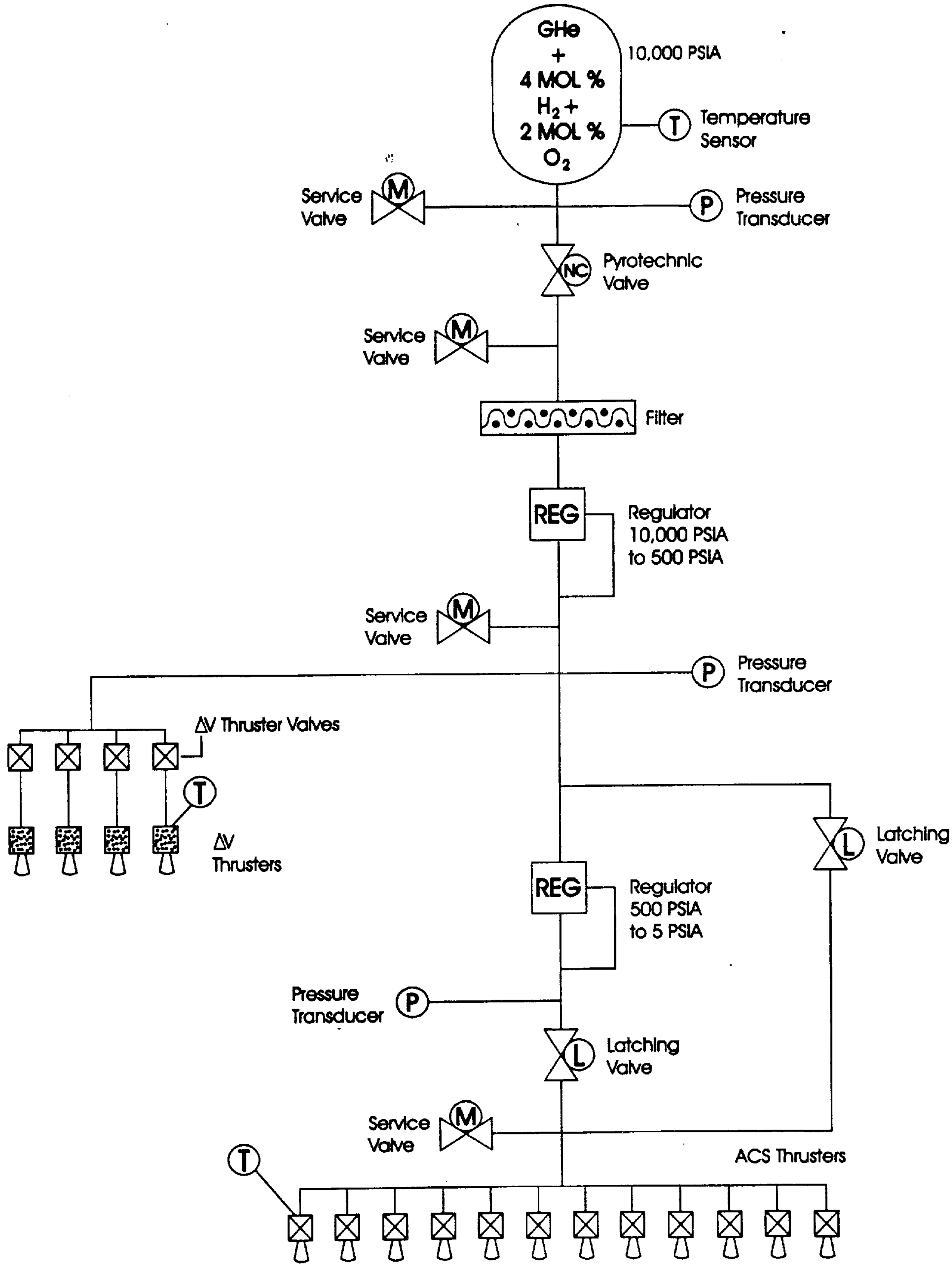


Figure 1.

Microspacecraft Hot-Helium Propulsion System Schematic Diagram to be used for additional secondary TVC for the ΔV burns and allows slewing and hovering at two different acceleration levels. The primary TVC for the ΔV burns is achieved by off-pulsing the ΔV thrusters. Figure 2 shows the arrangement of the ACS thrusters. Non-translational rotation about any axis is obtained by firing the thrusters in couples. Firing both of the thrusters that are perpendicular to a given face provides translation for slewing and hovering. The ACS thrusters do not benefit from heated helium due to the long transient heat-up time of the catalyst bed.

Table II shows the system requirements and the capability of the point design for the second-delivery spacecraft as well as the capability of the technology for use in other system designs.

Mass and power estimates and the technology basis for each component are shown in Table III.

HEATED HELIUM PERFORMANCE

The helium propellant is heated for ΔV burns by adding small amounts of hydrogen and oxygen to the inert gas. When the mixture is passed over a catalyst, water is formed exothermally. Within the safe, non-detonable limits of hydrogen and oxygen, the helium can be heated such that a specific impulse in excess of 3000 m/s (306 seconds) appears to be obtainable.

DIVERSITY OF PROPELLANTS

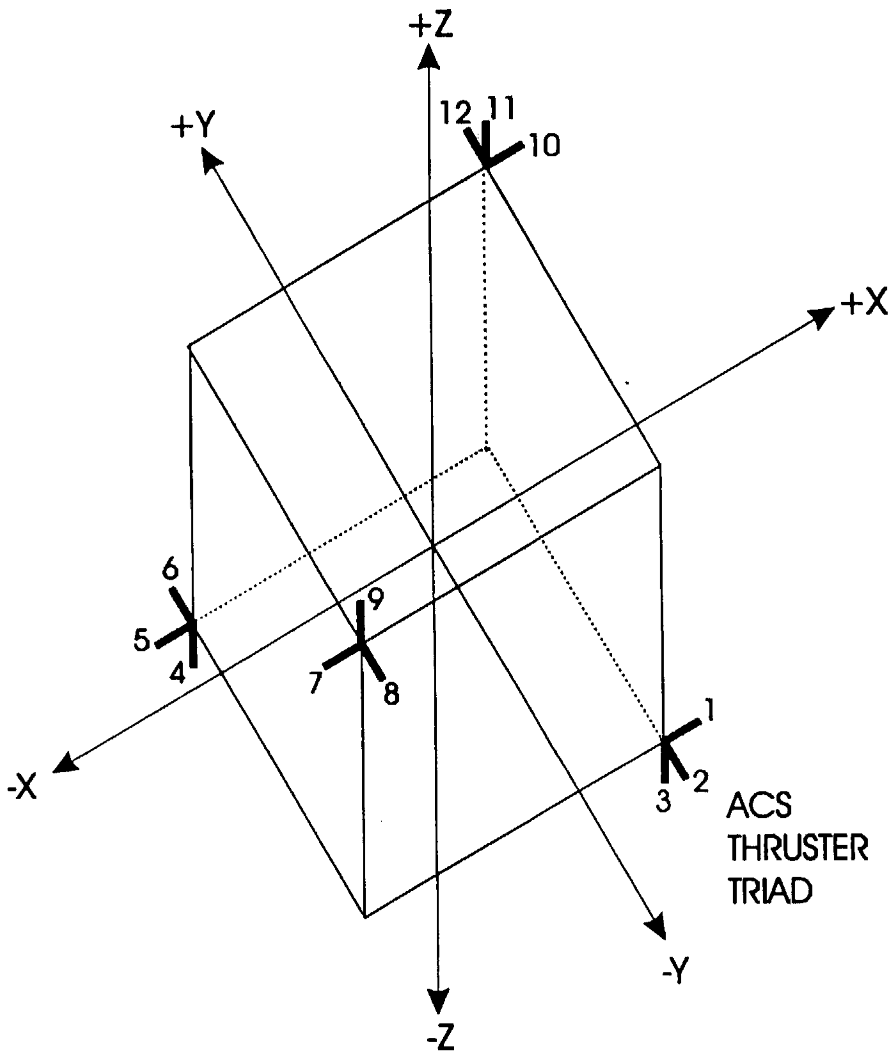
For a generic propulsion system for future undefined scientific micro/nanospacecraft, the chemical species of the thruster exhaust plumes is very important. For the second-delivery microspacecraft, the presence of hydrogen, oxygen and water in the plumes is not a problem. For those missions that might be looking for nitrogen, hydrogen, oxygen or water, the system can be operated as a cold-gas system using helium, nitrogen, oxygen or hydrogen gas. If the second-delivery tank does not provide enough impulse, a larger tank or a heavier gas can be used. Table IV shows the available ΔV and initial "wet" mass of the second-delivery microspacecraft for various gases.

ASSEMBLY AND TEST

All cleaning, assembly and testing of subassemblies, assemblies and the full system and all related operations are planned to be performed in a Class 100 cleanroom although future flight systems should use a Class 10 cleanroom. Figure 3 shows the preliminary proposed layout of this facility. Greater emphasis is needed towards contamination control. The cleanliness integrity of propulsion components needs to be maintained on the interior and exterior more than ever before for the new micro/nanospacecraft.

The system will use 3.2 mm (0.125 inch) outside diameter stainless steel tubing. The primary tube joining method will be automated orbital gas-tungsten-arc welding. Some brazed tube joints and even some adhesive bonded tube joints may be used as necessary. All tube joints will receive radiographic inspection, proof testing and visual inspection.

Periodic in-process leak tests will be performed on all assemblies and the full system. The system will be proof tested pneumatically behind a barricade.



MANEUVER	THRUSTERS USED
CLOCKWISE ROTATION ABOUT X-AXIS (+Z to +Y)	3 & 11 6 & 8
COUNTERCLOCKWISE ROTATION ABOUT X-AXIS (+Y to +Z)	2 & 12 4 & 9
CLOCKWISE ROTATION ABOUT Y-AXIS (+X to +Z)	3 & 9 5 & 10
COUNTERCLOCKWISE ROTATION ABOUT Y-AXIS (+Z to +X)	1 & 7 4 & 11
CLOCKWISE ROTATION ABOUT Z-AXIS (+Y to +X)	8 & 12 1 & 5
COUNTERCLOCKWISE ROTATION ABOUT Z-AXIS (+X to +Y)	7 & 10 2 & 6

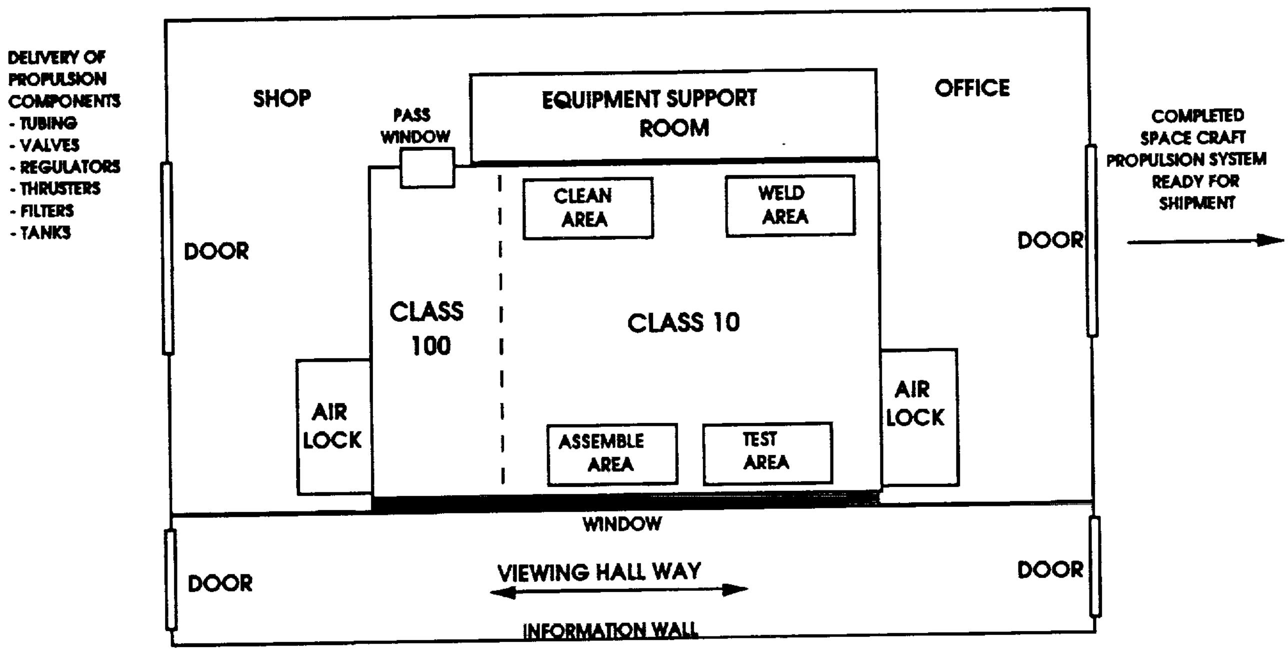
Figure 2.

ACS Thruster Arrangement

Figure 3.

MicroPropulsion Design Assembly and Test

- MPDAT -



This facility (Cleanroom) will comply to:
ISO - FDIS 14644-4, Design of Cleanrooms

TABLE II

Requirements vs Capabilities

REQUIREMENT	SOURCE	CAPABILITY (SECOND DELIVERY)	CAPABILITY (TECHNOLOGY)
50% Reduction in Dry Mass Over Current Technology	Systems Engineering	50% for Some Components (See Mass List)	50% for System
50% Increase in Performance	Systems Engineering	54% Increase (2492 m/s Isp vs. 1619 m/s Isp)	100% Increase (3257 m/s Isp vs. 1619 m/s Isp)
Total ΔV of 200 m/s for Initial Dry Mass of 21 kg.	Systems Engineering	200 m/s for Initial Dry Mass of 21 kg.	>200 m/s >21 kg.
Slew/Hover Total Impulse of 90 N-s	Systems Engineering	>90 N-s	>90 N-s
ACS Total Impulse of 2 N-s	Systems Engineering	>2 N-s	> 2 N-s
ACS Minimum Impulse Bit of 10^{-5} N-s	ACS/Comm/ SCI Systems	$<10^{-5}$ N-s	$<5\times10^{-7}$ N-s
Greater Than 200,000 ACS Pulses	Derived	One Million Pulses	One Million Pulses
ACS Thrust Level of 0.01 N per Thruster	ACS System	0.01 N per Thruster	0.05-0.0005 N per Thruster
Redundant 3-Axis Coupled Attitude Control	Systems Engineering	3-Axis Coupled Attitude Control Using 12 Thrusters	N/A
ΔV Thrust of 1.0 N per Thruster	Systems Engineering	1.0 N per Thruster	0.1 N-10 N per Thruster
Redundant ΔV Thrusters	Systems Engineering	4ΔV Thrusters	No Reasonable Limit
Multiple ΔV Burns	Systems Engineering	No Reasonable Limit	No Reasonable Limit
Regulator Step-Down Ratio	Derived	100:1	200:1

TABLE III

Mass and Power Estimates

Power	Part	No./S.S.	Mass/Part (g)	System Mass (g)	Basis
15 W per Thruster (Open) 5 W per Thruster (Hold)	Gas ΔV Thruster Valve	4	40	160	Millinewton Thruster
	*Gas ΔV Thruster	4	50	200	MAPS Technology
15 W per Thruster	Gas ACS Thruster/Valve Assembly	12	22	264	Millinewton Thruster
	He Tank	1	3650	3650	MAPS Technology
	Service Valve	4	12	48	Current Hardware
	Latching Valve	2	100	200	Mars Micromissions
	Filter	1	30	30	MAPS Technology Estimate
	Helium	1	2116	2116	Calculated from Assumptions
140 W for 5 ms	Pyro Valve	1	32	32	Current Hardware
1 W per Transducer	Pressure Transducer	3	180	540	Current Hardware
.06 W per Sensor	Temp Sensor	3	3	9	Current Hardware
	Regulator	2	300	600	DSST Technology Task Funding
	Tubing, Brackets, Fittings, etc.	1 SET	300	300	Estimated
			TOTAL	**8149**	
				(18.0 lbm)	

* Includes Catalyst Bed

TABLE IV

Effect of Propellant on ΔV

PROPELLANT	PROP. MASS [kg. (LB_M)]	INITIAL "WET" MASS [kg. (LB_M)]	ΔV [m/s (ft/s)]
Heated Helium (Baseline)	2.12 (4.66)	27.0 (59.5)	200 (656)
Heated Nitrogen	11.25 (24.80)	36.0 (79.3)	415 (1362)
Hydrogen	0.92 (2.03)	25.6 (56.4)	96 (315)
Helium	1.98 (4.36)	26.7 (58.9)	126 (414)
Nitrogen	11.25 (24.80)	36.0 (79.3)	270 (885)
Argon	19.02 (41.94)	43.7 (96.4)	291 (955)
Xenon	58.3 (128.6)	83.0 (183.0)	309 (1014)
Heated Argon	19.02 (41.94)	43.7 (96.4)	448 (1470)
Heated Xenon	58.3 (128.6)	83.0 (183.0)	513 (1683)

For flight missions, qualification testing consisting of vibration testing, functional testing and full-mission-duty-cycle testing in a vacuum environment will be performed on the full system.

HOT-GAS ΔV THRUSTERS

The hot-gas ΔV thrusters are derived from development started under the Mars exploration technology program, Reference 2. The catalyst bed design will be optimized by testing in a vacuum environment. The catalyst bed, thrust chamber and nozzle will be welded together and thoroughly insulated to obtain maximum performance and to minimize heating of the spacecraft. Specific impulse and thruster temperature will be measured in vacuum as a function of the quantity of hydrogen and oxygen doping to calibrate the theoretical model.

The ΔV thruster valve will be thermally isolated from the catalyst bed/thruster assembly to prevent overheating of the polymeric soft valve seat.

TANK

The helium tank technology is being developed for the Mars mission, Reference 2. For high-pressure tanks, the goal is a fifty percent reduction in the mass of equivalent state-of-the-art composite overwrapped tanks. A thin aluminum liner which provides hermetic sealing is overwrapped with graphite fiber composite to achieve this performance. Use of thin tank technology along with the performance gain obtained from heating the helium results in helium performance comparable to nitrogen, Table IV.

The tank for the second-delivery microspacecraft has a minimum volume at 690 bar (10,000 psid) of 0.023 m^3 (1405 in^3). The tank shape has ellipsoidal isotensoid heads with a short cylindrical section. The outside diameter and outside length at 690 bar (10,000 psid) are 356 mm (14.0 inches).

PRESSURE REGULATOR

Miniature pressure regulator technology is being developed for propulsion systems for future micro/nanospacecraft. Regulator designs meeting the requirements for these sets of operating conditions will be enabled by this technology. One basic design will be capable of the three operating conditions below:

HIGH-PRESSURE INLET, MEDIUM-PRESSURE OUTLET

- Pressure: 690 $_{BAR}$ (10,000 $_{PSIA}$) Maximum Inlet, 35 ± 0.7 $_{BAR}$ (508 ± 10 $_{PSIA}$) Outlet
- Flow Rate: 6 mg/s (1.3×10^{-5} lb_M/s) to 1.3 g/s (2.9×10^{-3} lb_M/s) of Helium

HIGH-PRESSURE INLET, LOW-PRESSURE OUTLET

- Pressure: 690 $_{BAR}$ (10,000 $_{PSIA}$) Maximum Inlet, 3.4 ± 0.07 $_{BAR}$ (50 ± 1 $_{PSIA}$) Outlet
- Flow Rate: 6 mg/s (1.3×10^{-5} lb_M/s) to 25 mg/s (5.5×10^{-5} lb_M/s) of Helium

MEDIUM-PRESSURE INLET, LOW-PRESSURE OUTLET

- Pressure: 35 $_{BAR}$ (508 $_{PSIA}$) Maximum Inlet, 0.34 ± 0.007 $_{BAR}$ (5 ± 0.1 $_{PSIA}$) Outlet
- Flow Rate: 2.7 mg/s (6.1×10^{-6} lb_M/s) to 11 mg/s (2.4×10^{-5} lb_M/s) of Helium

The pressure regulation accuracy is for an individual regulator.

All regulators will have a design leak-rate goal of less than 5×10^{-5} scc/s of helium and a mass goal of less than 300g (0.66 lb_M). Because the system will not have a significant volume between the regulators and the thrusters, lockup leak-tight integrity of the maximum degree will be required.

The first regulator to be built will be an engineering model which will receive sufficient testing to allow a qualification model to be built and tested. Completion of testing of the formal qualification model is scheduled for 2001.

THRUSTER VALVES

Several miniature solenoid valve design concepts are being investigated for the operating pressures and helium flow rate requirements for the various thrusters currently baselined for the micro/nanospacecraft missions. The estimated weight for one of these valves, excluding lead wires, is 19g and the goal for the maximum operating power is 7 watts. The valve mechanism is flexure guided, therefore, it has no sliding surfaces, making the seat interface the cycle-life-limiting factor. The design cycle-life requirement was set at 300,000 cycles, but we believe the realized capability will be at least 1,000,000 cycles at the conditions of the micro/nanospacecraft missions. The design requirement for the speed of response is less than 1 m/s to open and 1.5 m/s to close, but analysis indicates that perhaps 0.5 m/s can be achieved for both opening and closing for the micro/nanospacecraft missions.

ISOLATION VALVE (NORMALLY CLOSED AND NORMALLY OPEN)

Mechanisms which do not employ ordnance for actuation power are being explored, primarily to eliminate the typically large quantities of very small sized (under 25 micron) particulate injected into the pressurant fluid. This particulate population requires the addition to the system of a small-pore-size, large-holding-capacity filter in order to prevent leakage problems at downstream fluid control components such as pressure regulators and thruster valves. It is important that new mechanisms maintain the attributes of light-weight, low-pressure drop and hermiticity.

HEATED HELIUM VERSUS HYDRAZINE

For a microspacecraft the obvious competitor to a system using gas as a propellant is a system that uses liquid hydrazine as a monopropellant. Heated gas offers considerable advantage over hydrazine, particularly for a generic scientific satellite. One of the biggest issues for a hydrazine system is potential freezing of the propellant which is no issue with gas. Another major concern for a hydrazine system is propellant center-of-mass control, slosh control and gas-free expulsion. These require tank-size-and-shape-unique surface-tension devices or positive expulsion diaphragms or bladders which must be re-designed and re-qualified when the propellant load is significantly changed. A detailed comparison of a heated helium system to a hydrazine system is shown in Table V.

CONCLUSION

Use of a single propulsion system that provides heated gas for ΔV maneuvers and cold gas for minimum-impulse-bit ACS and TVC maneuvers offers many advantages such as mass, versatility and performance over competing types of propulsion systems for generic multiple-use scientific micro/nanospacecraft for both earth satellites and interplanetary missions.

TABLE V

Comparison of Heated Helium to Hydrazine

PARAMETERS	HOT-GAS SYSTEM	HYDRAZINE SYSTEM
Performance	3257 m/s (332s) Isp (Steady State) 1619 m/s (165s) Isp (Pulse Mode)	~2109 m/s (215s) Isp (Steady State) 589 m/s (60s) Isp (Pulse Mode)
System Mass/Packaging Volume	Superior Below ~200 m/s ΔV and Dry Mass Up to ~30 kg.	Superior From ~200 to ~2000 m/s ΔV and Dry Masses Up to ~75 kg. Above These Conditions Bipropellant Systems Are Superior
Variability of Thrust Level	Any Thrust from 1×10^{-3} N to Greater Than 50 N Without Re-qualification	Limited Number of Qualified Thrusters Between 1 N and 50 N
Variability of Propellant Load	Longer/Shorter/Lower Pressure Propellant Tank can be Used Without Re-qualification	Tank-Size Uniqueness of Expulsion Device Requires Re-qualification
Fine Pointing Control	Minimum I_{BIT} ~5×10^{-7} N-s	Minimum I_{BIT} ~5×10^{-5} N-s
Spacecraft/Site Contamination	He, H_2, O_2, H_2O - Can be Limited to N_2, A, Xe or He at Some Performance Penalty	N_2, H_2, NH_3
Center-of-Mass Control	Does Not Require Active Control - Slosh Not an Issue	Active Control (Surface Tension, etc.) Required as well as Slosh Control
Heater Power	None Required	Considerable Power Required
Expulsion Control	None Required	Tank-Size-Unique Propellant Management Device Required

TABLE V (cont.)

Comparison of Heated Helium to Hydrazine

PARAMETERS	HOT-GAS SYSTEM	HYDRAZINE SYSTEM
Leakage Susceptibility	Soft Seat Valves (~1×10^{-4} scc/sec.)	Soft Seat Valves (~1×10^{-4} scc/sec.)
Toxicity	Non-toxic	Toxic
Flammability	Non-flammable	Flammable
Safety	Safe Up to About 12 MOL Percent Hydrogen	Only Concern is Catalytic Decomposition

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